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MEMORANDUM

AIR-COOLED TURBINE BLADES WITH TIP CAP FOR
IMPROVED LEADING-EDGE COOLING

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SPACE ADMINISTRATION

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SUMMARY

An investigation was conducted in a modified turbojet engine to determine the cooling characteristics of the semistrut corrugated air-cooled turbine blade and to compare and evaluate a leading-edge tip cap as a means for improving the leading-edge cooling characteristics of cooled turbine blades.

Temperature data were obtained from uncapped air-cooled blades (blade A), cooled blades with the leading-edge tip area capped (blade B), and blades with slanted corrugations in addition to leading-edge tip caps (blade C). All data are for rated engine speed and turbine-inlet temperature (1660° F). A comparison of temperature data from blades A and B showed a leading-edge temperature reduction of about 130° F that could be attributed to the use of tip caps. Even better leading-edge cooling was obtained with blade C. Blade C also operated with the smallest chordwise temperature gradients of the blades tested, but tip-capped blade B operated with the lowest average chordwise temperature. According to a correlation of the experimental data, all three blade types could operate satisfactorily with a turbine-inlet temperature of 2000° F and a coolant flow of 3 percent of engine mass flow or less, with an average chordwise temperature limit of 1400° F. Within the range of coolant flows investigated, however, only blade C could maintain a leading-edge temperature of 1400° F for a turbine-inlet temperature of 2000° F.

INTRODUCTION

The advantages and problems of turbine blade cooling have been discussed in many reports and publications (e.g., those listed in the bibliography of ref. 1). Two of the most difficult problems associated with turbine cooling are structural integrity and adequate cooling of the

leading edge. The structural integrity of the basic cooled blade of this report (semistrut, corrugated, air-cooled) has been proved at rated operating conditions and is reported in reference 2.

Leading-edge cooling is made difficult by three factors: (1) the heat-transfer rate to the blade is higher at the stagnation point (on the leading edge) than at any other point on the cooled blade; (2) it is difficult to provide adequate internal cooling surface area in the leading-edge region to carry away the heat transferred from the gas to the blade; and (3) the cooling air discharging from the tip of the blade discharges against a higher pressure at the leading edge than at any other portion of the blade, and this reduces the flow rate to the leading-edge region. Research on the first two problems is reported in references 3 to 5. The leading-edge radius was increased to reduce gas-to-blade heat-transfer rates and at the same time improve the flow and surface-area conditions inside the leading edge. However, this improvement in leading-edge cooling can result in a penalty in aerodynamic performance. Leading-edge film cooling and improved cooling by conduction where the inside of the blade was copper clad were also investigated. These methods resulted in improved leading-edge cooling, but the structural reliability was poor. The slots for film cooling resulted in rapid failure under engine operating conditions. The copper cladding was both heavy and subject to rapid oxidation at the required blade operating temperatures.

A method of overcoming the third leading-edge problem, that is, discharging cooling air against the high pressure at the leading edge, is the research discussed herein. The investigation was conducted on semistrut corrugated air-cooled blades similar to those described in reference 2. Two internal-corrugation configurations were investigated that were designed either to have high internal surface area at the leading edge or to direct a maximum amount of cooling air to the leading edge. In addition, tip cap arrangements were investigated that were designed to let the cooling air to the leading edge discharge into a lower pressure region, which would result in higher coolant flow rates to the leading edge, particularly at the low flow rates desirable for best engine performance. The experimental investigation was conducted at rated engine speed (1300 ft/sec tip speed) and turbine-inlet temperature (1660° F). The experimental data were analytically extrapolated to determine turbine blade operating temperatures for turbine-inlet temperatures of 1800° and 2000° F.

APPARATUS AND INSTRUMENTATION

Blades

The basic construction of the blades used for this investigation is described in reference 2 and shown in figure 1. The struts were machined from standard S-816 forged turbine blades, and the shell components and corrugations were made from L-605 sheet. The blade assembly was brazed together (in a vacuum furnace) with a high-temperature braze.

The temperature data reported herein are for three pairs of cooled blades, one pair of blades as described in reference 2 and shown in figure 1, and two pairs that were modifications of this basic design. The basic blade will be hereafter referred to as the uncapped air-cooled turbine blade or blade A. This blade had the corrugations extending as far as possible into the leading edge to obtain a maximum of augmented surface area in this region.

The construction of the second pair of blades was the same as that of blade A except that the leading- and trailing-edge tip corners of the corrugations and inner shell were removed on a 45° diagonal before blade assembly (fig. 2). These tip corners of the corrugations were removed so as to provide a small plenum chamber for the expended cooling air to exhaust into before moving through the blade tip. A 0.020-inch-thick piece of L-605 was fitted and brazed as a leading-edge tip cap (fig. 2). The chordal length of the capped portion, that portion that was forced to exhaust to the trailing edge, was approximately 20 percent of the chord. This blade will be referred to as the leading-edge tip-capped cooled turbine blade or blade B.

The third pair of blades investigated were leading-edge tip-capped blades with slanted corrugations (fig. 3). The corrugation section was cut so that the corrugations were approximately 45° to the leading edge of the blade. All cooling air was brought across the strut and up the leading edge through the corrugations to the trailing-edge tip section. This corrugation arrangement was devised to induce the maximum cooling flow rate to the leading edge. This blade was also a brazed assembly. The tip cap shown in figure 3 was fitted on top and welded to the shell. It extended for approximately 50 percent of the chord. This blade type will be referred to as the slanted-corrugation tip-capped blade or blade C.

Engine

The data reported herein were obtained from the test blades when they were operated in a jet engine with a single-stage turbine. The blade installation is described in reference 2. The turbine was modified

to supply cooling air to two test blades located diametrically opposite one another. Laboratory air was supplied to the blades through a special modified tailcone assembly shown in figure 4. The details of the modification are described in reference 6.

Instrumentation

Blade temperature measurement. - The thermocouples were located on the outer shell and the strut of the test blades, as noted in figures 5 to 7. Temperature measurements were concentrated in the region at the end of the strut because reference 2 indicates this to be the critical region for this type of blade. The thermocouples on the shells were of the NACA embedded type held in the grooves with ceramic cement (ref. 7). The thermocouples on the struts were spotwelded to the strut. An NACA 24-ring (12-thermocouple) thermocouple slip-ring assembly was used to complete the circuits to the recording instruments.

Pressure measurement. - Static-pressure measurements were made in the turbine shroud band directly over the turbine blades. The measurement positions were 1/4 inch ahead of the leading edge, the leading edge, 25 percent chord, midchord, 75 percent chord, the trailing edge, and 1/4 inch behind the trailing edge. A schematic view of this system is shown in figure 8(a).

PROCEDURE

After two blades of a given type were installed in the turbine wheel, the tailcone assembly was installed. With the blade cooling air-flow set at a maximum, the engine was started and accelerated to the rated speed of 11,500 rpm and a turbine tip speed of 1300 ft/sec. The clamshell exhaust nozzle was closed until the rated exhaust-pipe temperature of 1260° F (inlet gas temperature of approximately 1660° F) was reached. Temperature data were obtained first with the maximum coolant flow rate and then with reduced coolant flows. After all temperature data were obtained with coolant flows from maximum to zero, a cover was welded over the entire tip area of each test blade and the engine again was operated at rated conditions to determine the leakage (cooling air that did not go through the blades). The cooling-air supply pressure in the tailcone was set at the same values as for the coolant-flow temperature data. The flow registered was assumed to be the leakage around the seal and the bases of the test blades. The data from these leakage tests were used to correct the coolant flows for the heat-transfer data.

RESULTS AND DISCUSSION

The data for various thermocouple positions and coolant-flow rates for the six blades tested are shown in figures 5 to 7. Incomplete data, such as in figure 6 were the result of thermocouple failures. The variation in temperature between blades of a given pair was probably due to variations in manufacture and coolant flow.

Figure 5 presents the temperatures for the uncapped A blades, for an uncooled conventional solid blade, and for the cooling air just before it entered the blade base. The maximum solid-blade temperature reached at the midchord and the spanwise position corresponding to the end of the strut of the cooled blades was approximately 1400°F . Excellent agreement is apparent at the same locations on blades A-1 and A-2. The most significant point to observe, however, is the poor cooling of the leading edge at low flow rates. The leading-edge temperature is lowered only 90°F (1370° to 1280°F) with a flow of $1\frac{1}{2}$ percent of engine mass flow even though the incoming coolant is 1000°F colder than the leading-edge metal temperature. Coolant flow in percent of engine mass flow will hereafter be referred to as percent flow. The same lag is also somewhat apparent at the midchord-midspan position both in the shell and on the strut.

Discolorations of shielded parts of blades tested to failure (investigation reported in ref. 2) and blades that were run for long time periods was evidence that, in addition to high temperatures in the leading edge, hot combustion gases may have circulated in the leading-edge section, mixed with cooling air, and then passed out the trailing-edge region. These indications first led to the research which is the basis of this report. From these observations, it was assumed that the static exhaust gas pressure in the leading-edge region at the blade tip was probably greater than the coolant supply pressure at low flow rates.

Data obtained to indicate qualitatively the static exhaust gas pressures over the blade tip are presented in figure 8(a). These data were obtained from static-pressure taps located in the turbine shroud as schematically shown in the figure. The static-pressure profile measured is assumed to be indicative of the pressure profile immediately above the tips of the rotating blades. The values of these pressures would include the effects of such variables as turbine blade tip clearance, cooling air exhausting from the tips of cooled blades (particularly if all the blades were cooled), and boundary-layer conditions. Considering the chordwise pressure profile in figure 8(a), it can be concluded that the coolant pressure required at the blade tip to force cooling air through the leading edge is greater than at the trailing edge; therefore, at low flows the trailing edge will cool more effectively than the leading edge. Presented in figure 8(b) is the cooling-air supply pressure measured for the

values of coolant flow. These data are for the three blade types reported herein. The static pressure of the coolant was measured at the hub of the turbine rotor. These pressures differ from the blade tip pressures because of the pressure rise from the centrifugal pumping effect in the blades and radial coolant supply passages and the pressure drop through the blade. Actual measurement of cooling-air pressures at the blade tip were not made because adequate instrumentation for such measurements has not been developed. The difference in pressure required for the three blade types for a given coolant flow is due to the difference in the pressure drop through the blades. Blade C had the largest pressure drop.

The cooling-air pressure at the blade tip must be at least as great as the exhaust gas static pressure in order for cooling air to exhaust at the blade tip. If the leading-edge tip region is capped and provisions are made for transporting the expended leading-edge cooling air to the lower gas pressure region at the trailing edge, blade cooling should greatly improve at low flows. This is the reasoning that led to the design of blade B (fig. 2). The results are shown in figure 6. Comparison of figures 5 and 6 shows that at 1 percent flow the average temperature at the leading edges of the capped blades is about 130° F lower than at the same location of the uncapped blade A-1. At $2\frac{1}{2}$ percent flow the temperature difference is small.

From figures 5 and 6 it is apparent that the midchord and particularly the trailing edges are cooled much more than the leading edge. If the fresh cooling air can be introduced to the leading-edge section first, where the heat flux into the blade is a maximum, further improvements in blade cooling should be achieved. This feature is the design principle behind blades C (fig. 3). The air is passed first over the base of the strut where it picks up very little heat, then into the leading-edge region, next diagonally across the blade, and finally up the trailing edge and out the blade tip at the trailing edge, where the main-gas-stream static pressure is lowest. The test results of this design are presented in figure 7. Comparison of figures 5 and 7 shows an average decrease of about 180° F in leading-edge temperatures on the slanted-corrugation blades as compared with the uncapped blade A-1 at 1 percent flow, and at $2\frac{1}{2}$ percent flow the leading-edge temperature was 80° F lower.

The leading-edge temperature comparison can be seen better in figure 9. The temperatures for the two blades of designs B and C were averaged. The improvement in leading-edge cooling exhibited by the tip-capped blades B and C is self-evident. With a coolant flow of 2.5 percent the leading-edge temperature of blade C was reduced to approximately 350° F below that of the uncooled solid blade. The chordwise temperature

distribution for the three blades is given in figure 10. At coolant flows from 1/2 to 3 percent the slanted-corrugation blade (blade C) had the lowest temperature gradient of the three blade types investigated. Blade B had the lowest average chordwise temperature. The relative merit of a low leading-edge temperature with a minimum chordwise temperature gradient and a higher leading-edge temperature with the lowest possible midchord and trailing-edge temperatures (low average chordwise temperature) would have to be determined for each individual blade design. The data herein illustrate that it is practical to design air-cooled blades that have very low chordwise temperature gradients. A uniform chordwise temperature gradient would be desirable in keeping the thermal stresses to a minimum.

For the brazed blade structure of many components reported in reference 2 and herein, it is desirable to operate with a minimum leading-edge temperature and an associated minimum chordwise temperature gradient.

Figure 11 was plotted to indicate the spanwise temperature distribution at coolant flows of 1 and 3 percent for those points where data are available; only one thermocouple was installed on the leading edge of the uncapped blades. Also included on the graph is the design temperature, the actual spanwise temperature distribution measured at midchord on uncooled solid blades and used in reference 2 for designing the uncapped blade (blade A) for use at higher turbine-inlet temperatures. The gradient for blade C was approximately the same as the design gradient. The steeper gradient exhibited by the capped blade is not poor from the standpoint of static strength, however, because higher temperatures can be tolerated near the blade tip where stresses are low. The important point is the magnitude of the temperature in the base of the strut and in the blade shell near the end of the strut. The base temperatures of all the struts are very safe (figs. 5 to 7); in fact, at a coolant flow of $2\frac{1}{2}$ percent the measured strut temperatures were a minimum of 700° F below the design temperature of 1200° F (ref. 2) for the strut base of these blades. From figure 11 it is apparent that at 1-percent flow the leading edge of the uncapped blade shell is operating at design temperature with a turbine-inlet temperature of approximately 1660° F (rated for the uncooled blades).

COOLING POTENTIAL AT TURBINE-INLET TEMPERATURES OF 1800° AND 2000° F

The correlation procedure presented in reference 8 was used to project the experimental data obtained at rated engine conditions (turbine-inlet temperature, 1660° F; engine speed, 11,500 rpm; turbine tip speed, 1300 ft/sec) to elevated turbine-inlet temperatures of 1800° and 2000° F. The average of the chordwise temperatures presented in figure 10 was used as the basis for the correlation. These average chordwise temperatures plus the correlation results are presented in figure 12.

Blade B would operate with a lower temperature or more efficiently at all coolant flows. With turbine-inlet temperatures of 1800° and 2000° F and coolant flows above approximately 2 percent, blade C operates with the highest average chordwise temperature.

The structural integrity of this basic turbine blade structure was proven and is reported in reference 2. The blades operated satisfactorily without cooling air, or at a blade temperature of approximately 1400° F. Figure 12 shows that with a turbine-inlet temperature of 1800° F and a maximum assumed allowable average blade temperature of 1400° F all three blade types could operate satisfactorily with coolant flows of approximately 1.15 percent. With a turbine-inlet temperature of 2000° F blades A, B, and C could operate with coolant flows of about 2.5, 1.7, and 3 percent, respectively. Considering only the average chordwise temperature in the shell at the end of the strut, blade B is the most efficient blade investigated.

Reference 8 also extends the correlation to a determination of local blade temperatures. Therefore, this correlation was used to estimate the leading-edge temperature at the end of the strut for turbine-inlet temperatures of 1800° and 2000° F. Figure 13 presents these data. Also plotted for comparison are the experimental data for rated engine conditions, for which the assumed allowable leading-edge blade temperature is 1400° F. With a turbine-inlet temperature of 1800° F, blades A, B, and C would require coolant flows of approximately 2.6, 1.4, and 1 percent, respectively. At a turbine-inlet temperature of 2000° F, blade C requires a coolant flow of approximately 3.6 percent. Furthermore, blade C is the only blade that could operate with an allowable leading-edge temperature of 1400° F. Therefore, when the leading-edge temperature is considered as an operating limit, blade C is the most efficiently cooled blade.

It should also be noted that in figure 13 the leading-edge temperatures of blades A and B approach one another at increased coolant flows. These data prove the value of the tip cap. As the cooling-air supply pressure is increased, the cooling effectiveness of blade A improves until the coolant flow in the leading edge of the uncapped blade is equal to the flow in the capped blade. Thus with increased coolant flows the two blades would operate at the same leading-edge shell temperatures.

For engine operation at an elevated turbine-inlet temperature of 2000° F, blade B would be most desirable because of its low average chordwise temperature, low pressure drop, and ease of fabrication. If a low chordwise thermal gradient and a low leading-edge temperature were most important, blade C would be most desirable. Practically, a blade could be designed with the corrugations oriented and shaped so that the cooling characteristics would fit the specific application.

SUMMARY OF RESULTS

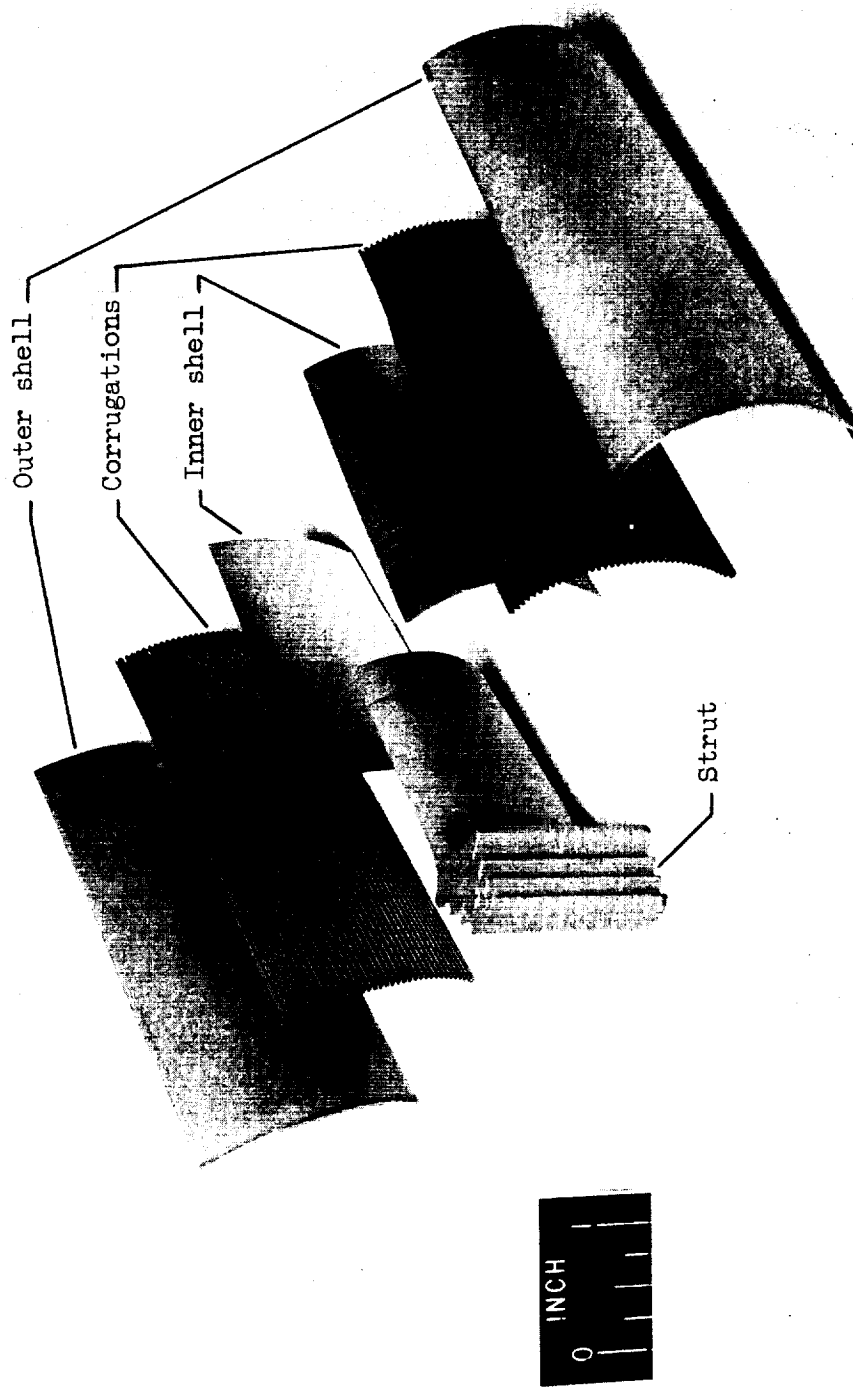
The leading edge of air-cooled turbine blades will not cool efficiently until the coolant supply pressure is greater than the exhaust gas pressure in the tip region, where the expended coolant is exhausted. The tip caps proposed herein permit the leading edge of the blade to cool more effectively with low coolant flows because the coolant is exhausted to the lower pressure region. The results of the investigation can be summarized as follows:

1. The reduction in leading-edge temperatures through use of tip caps was most effective at coolant flows below approximately 2 percent of engine mass flow. A leading-edge temperature reduction of up to 130° F was attributable to the tip caps.
2. Tip-capped blade B with radial corrugations operated with the lowest average chordwise temperature.
3. The slanted-corrugation blade C operated with the lowest leading-edge temperature and also with the smallest chordwise temperature gradient. With a coolant flow of $2\frac{1}{2}$ percent of engine mass flow the leading-edge temperature was approximately 350° F below that of the uncooled blade.
4. With a coolant flow of $2\frac{1}{2}$ percent of engine mass flow the measured strut temperature at the base of all blades was a maximum of 500° F, while the safe design temperature was 1200° F.
5. According to a correlation of the experimental data, all three blade types could operate satisfactorily with a turbine-inlet temperature of 2000° F and a coolant flow of 3 percent of engine mass flow or less, with an average-chordwise-blade-temperature limit of 1400° F.
6. Within the range of coolant flows investigated, only blade C could maintain a leading-edge temperature of 1400° F with a turbine-inlet temperature of 2000° F. A coolant flow of 3.6 percent would be required.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, November 14, 1958

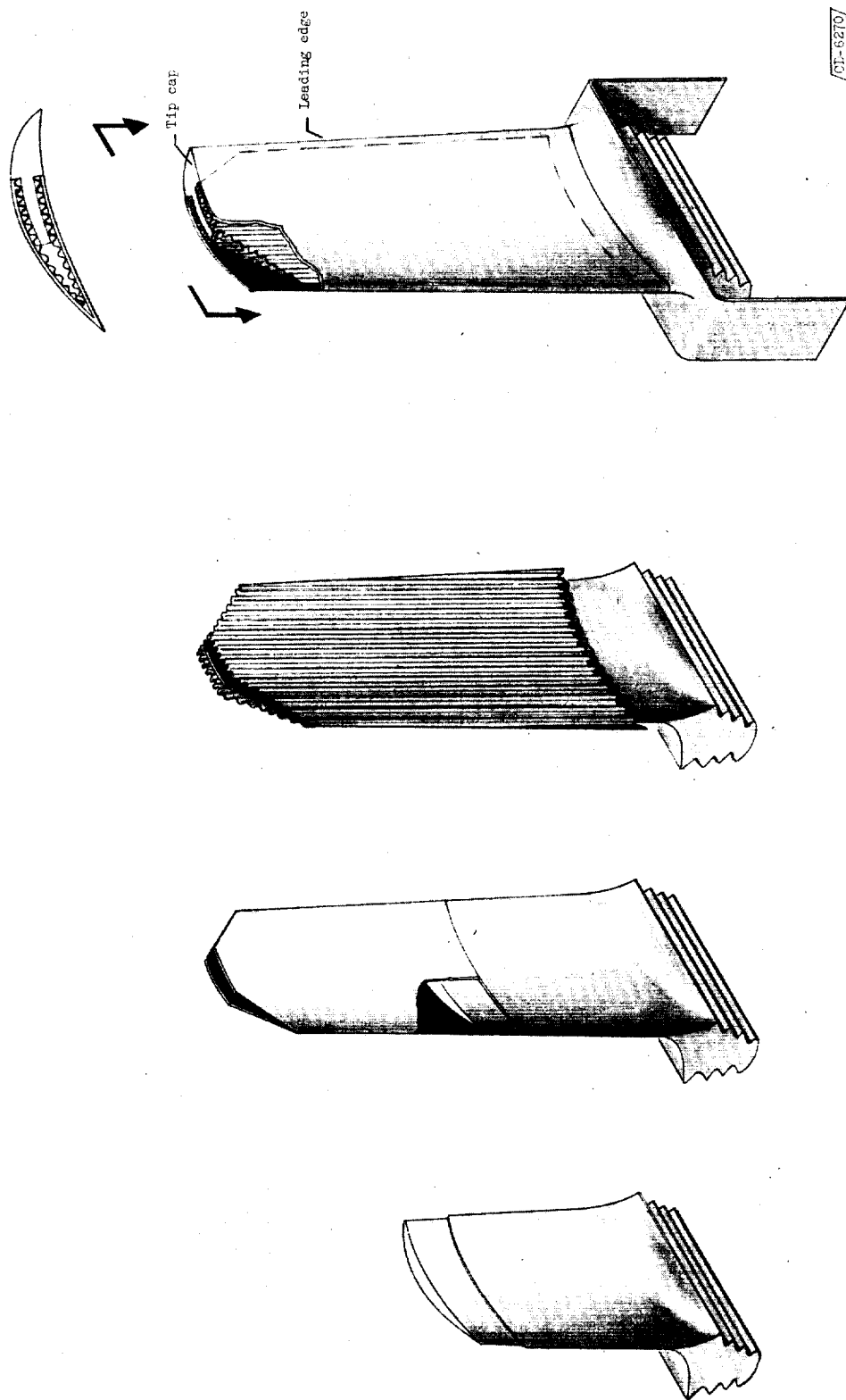
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Figure 1. - Exploded view of components of semistrut corrugated air-cooled turbine blade.



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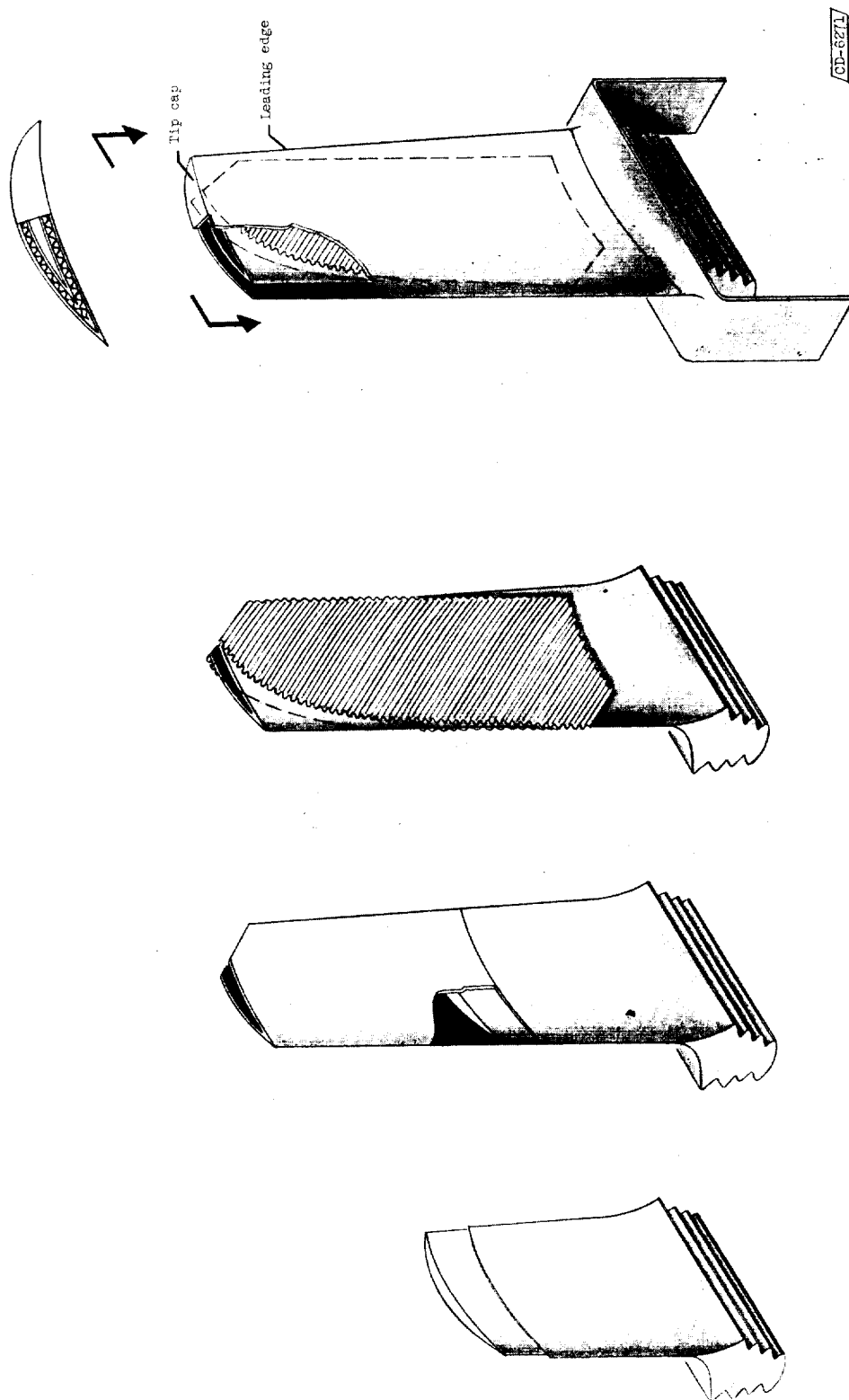


Figure 3. - Schematic view of slanted-corrugation tip-capped blade (blade C).

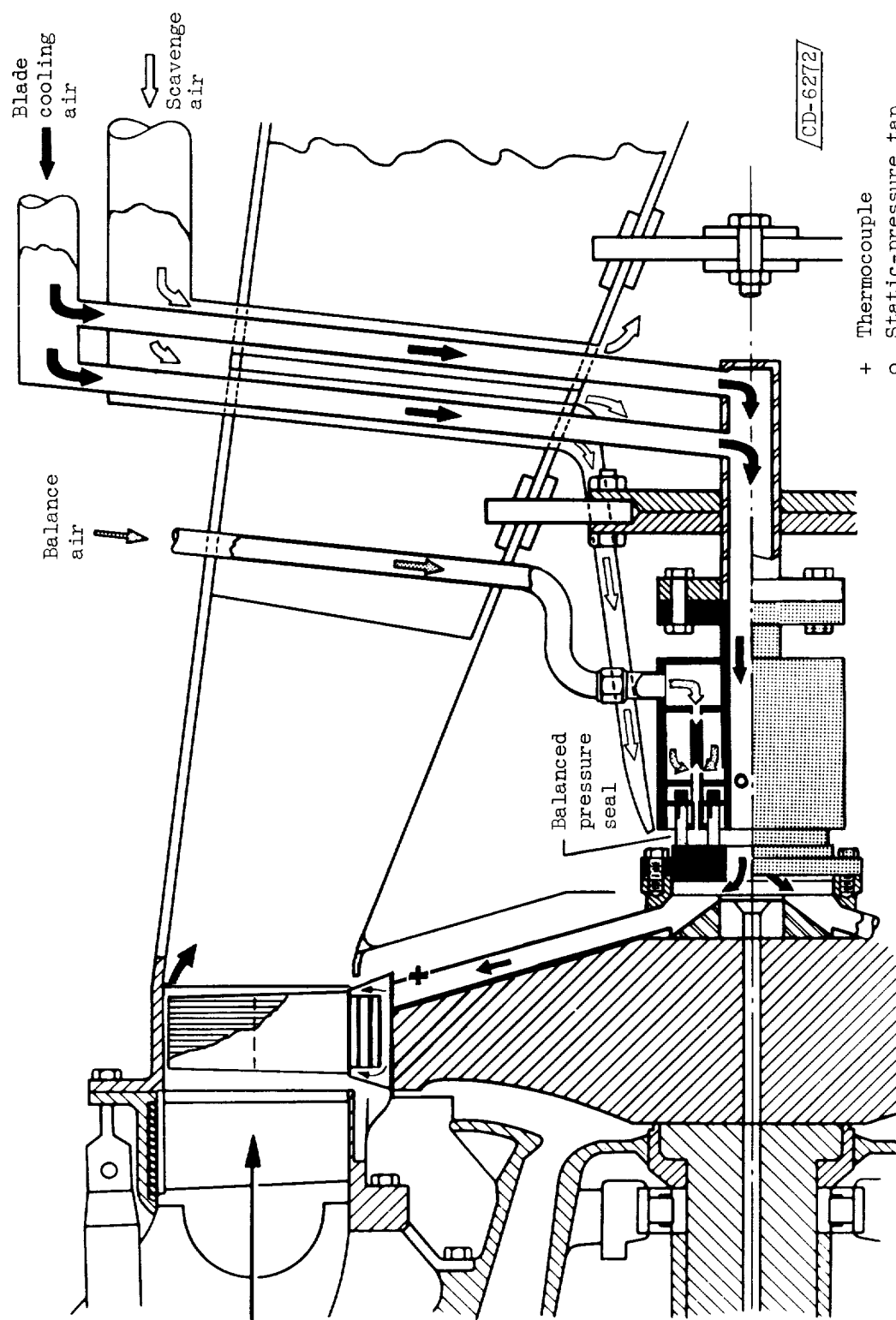


Figure 4. - Cooling-air induction system installed in tailcone of turbojet engine modified for turbine-cooling research.

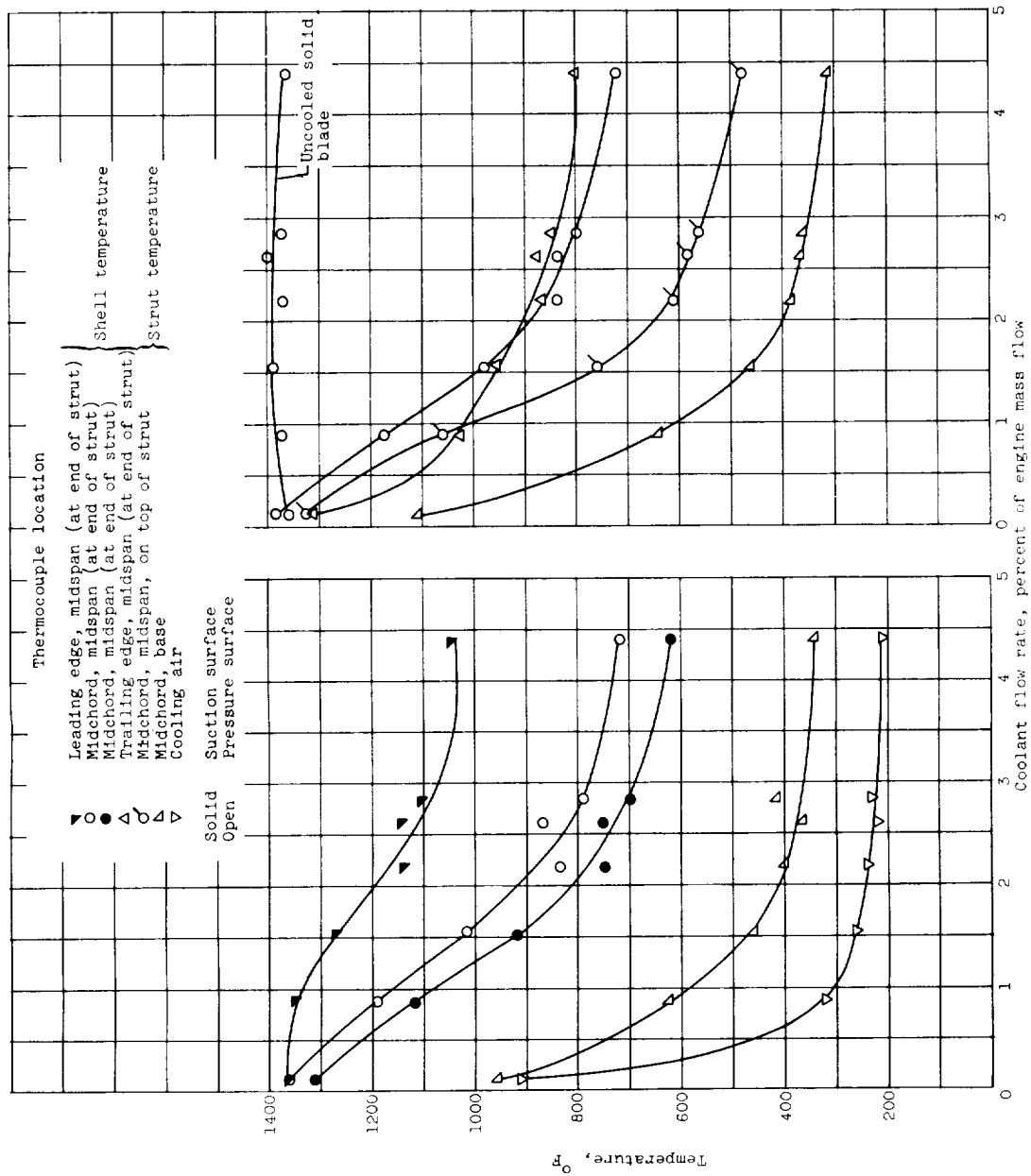
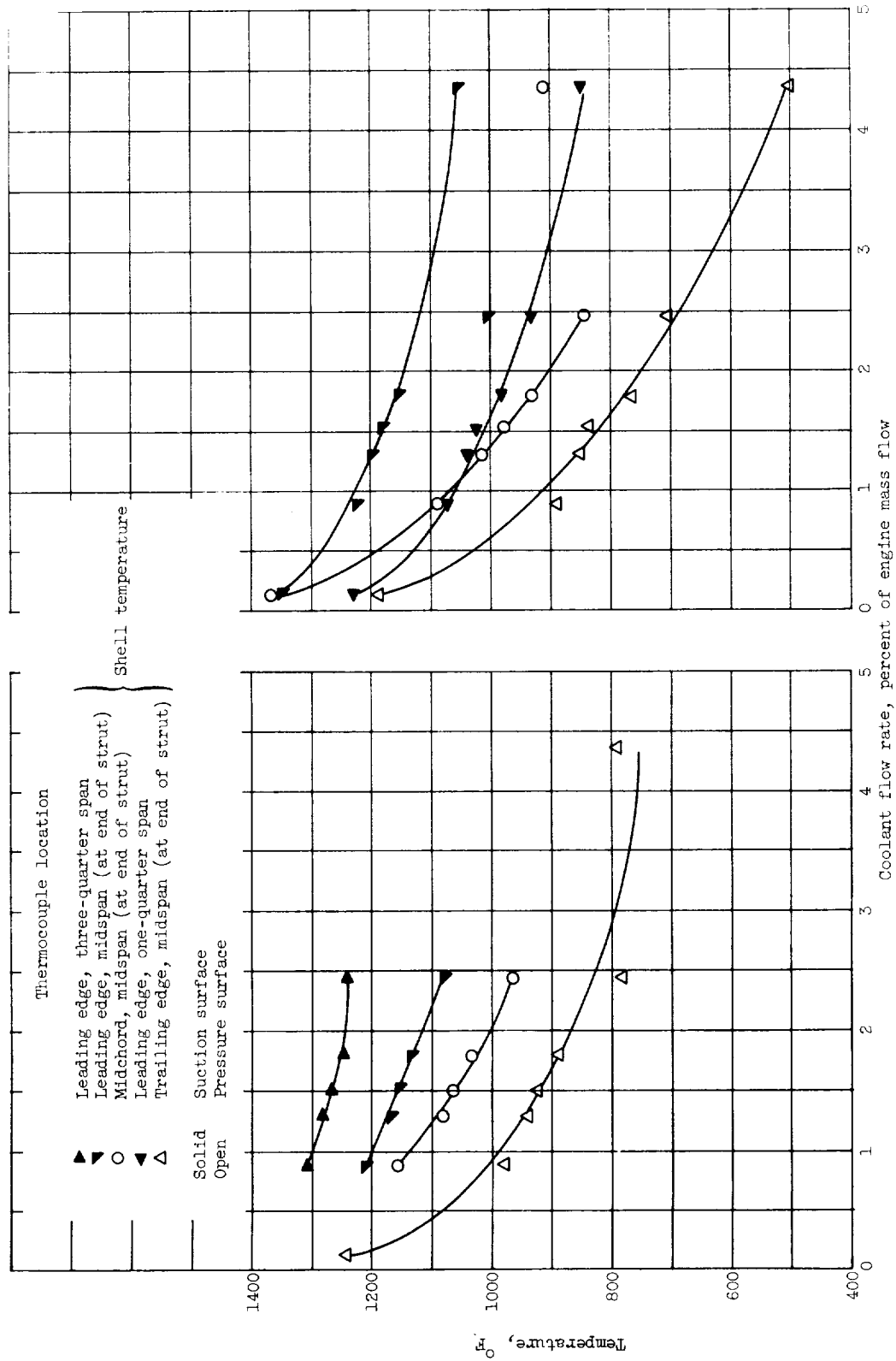


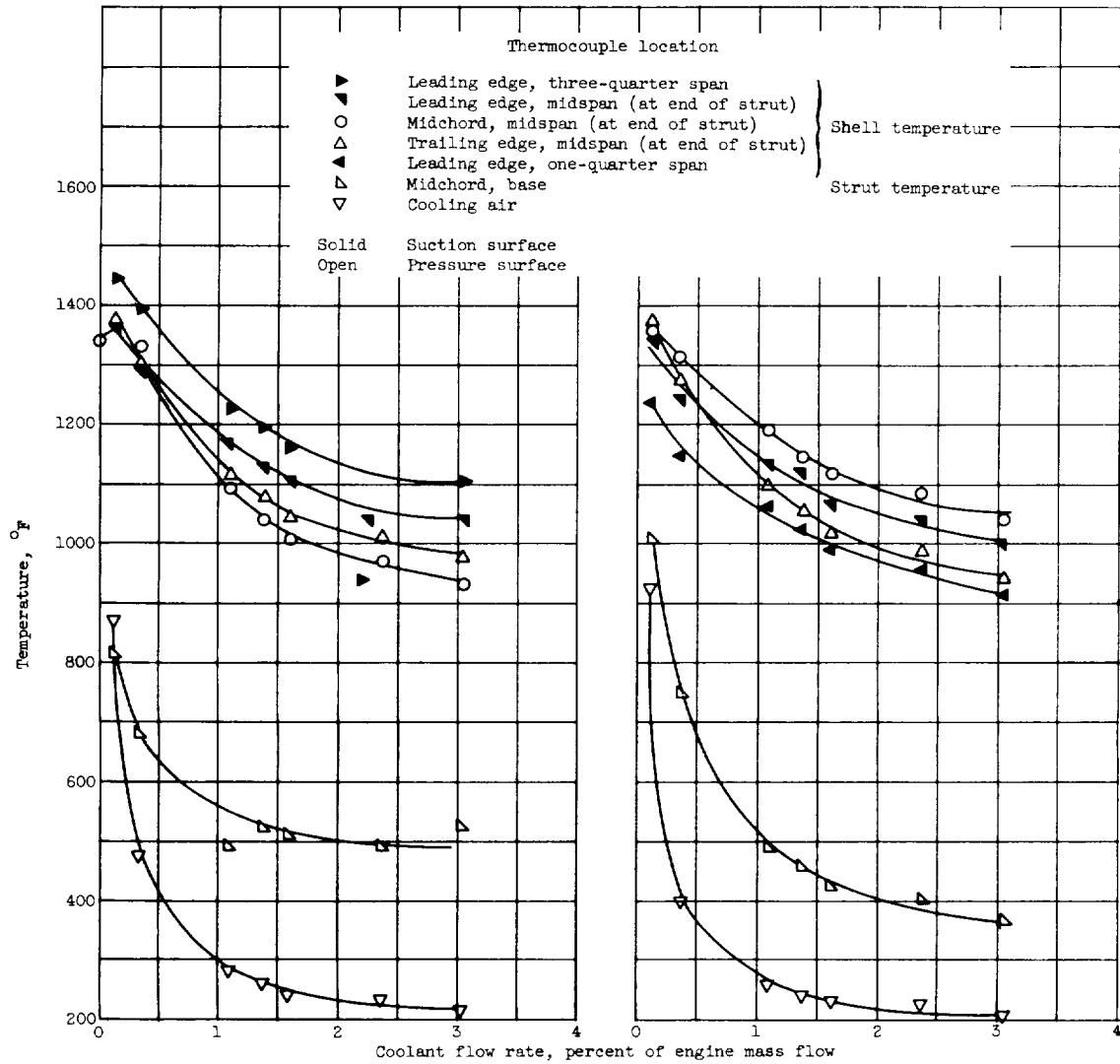
Figure 5. - Measured temperatures for uncapped semistrut corrugated turbine blade (blade A).



(a) Blade B-1.

(b) Blade B-2.

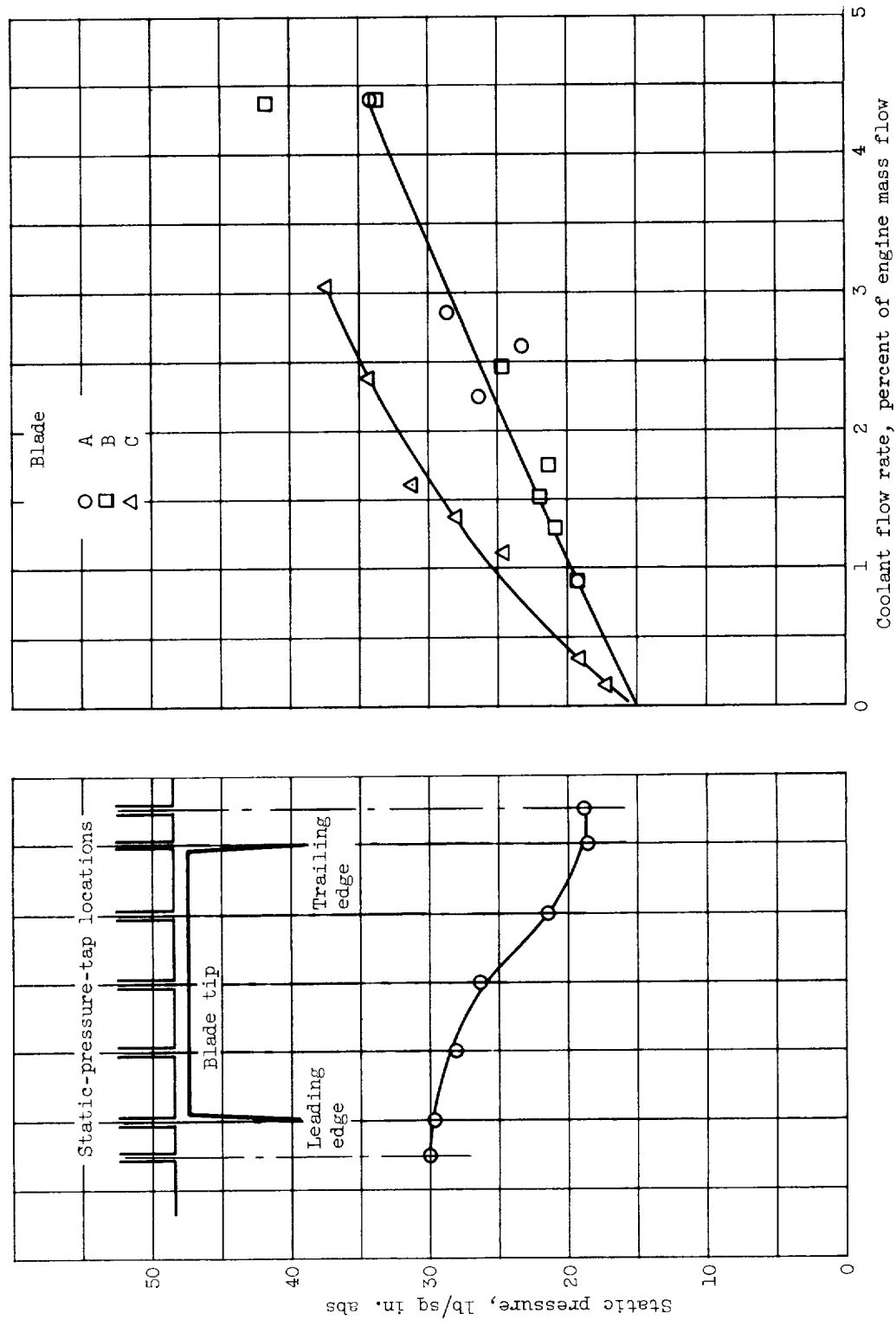
Figure 6. - Measured temperatures for leading-edge tip-capped blade (blade B).



(a) Blade C-1.

(b) Blade C-2.

Figure 7. - Measured temperatures for slanted-corrugation tip-capped blade (blade C).



(a) In turbine shroud.
Figure 8. - Static-pressure measurements in turbine shroud and in cooling-air supply.
(b) In cooling air.

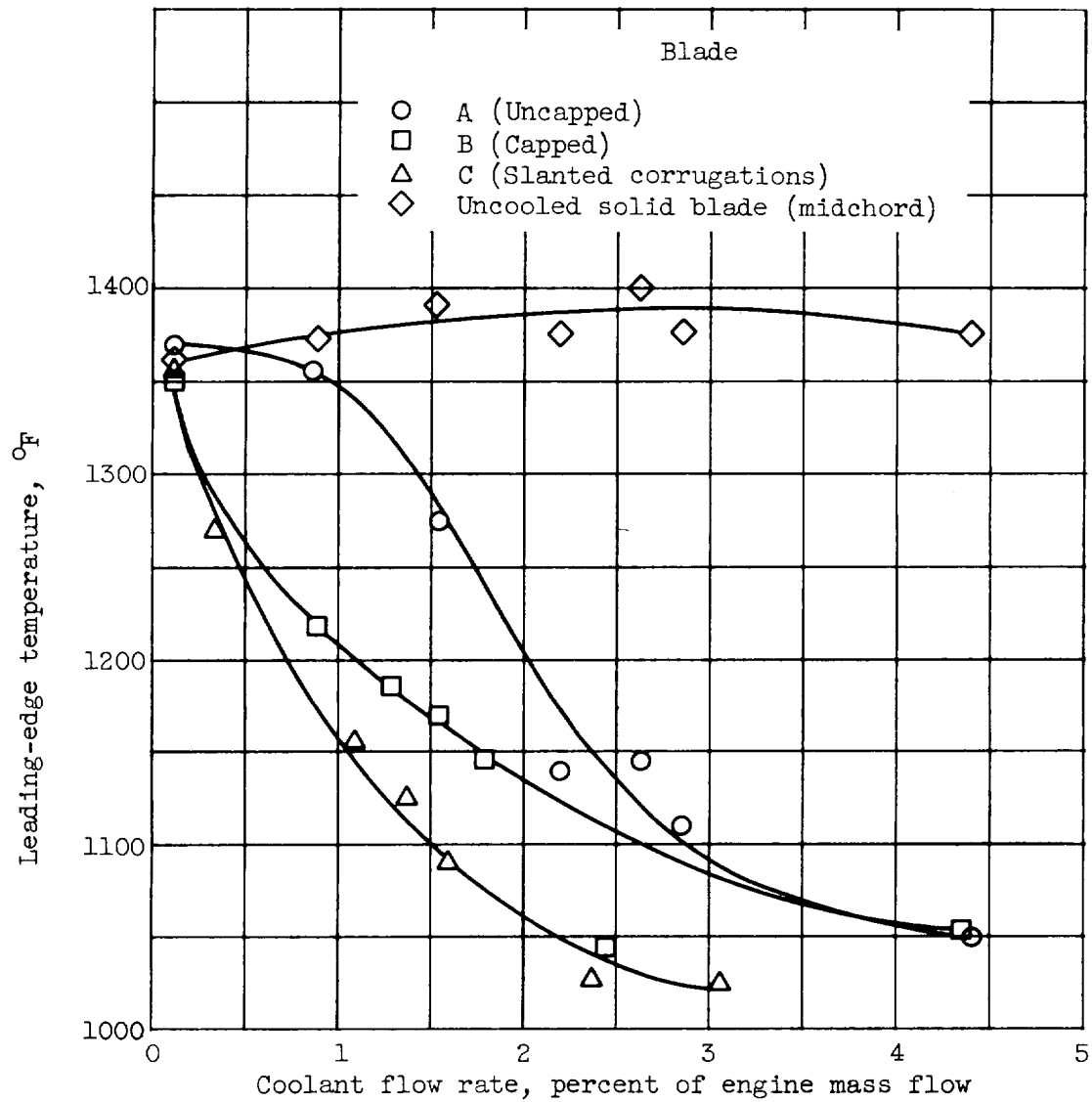


Figure 9. - Measured leading-edge midspan shell temperatures for three blade types investigated and uncooled solid blade.

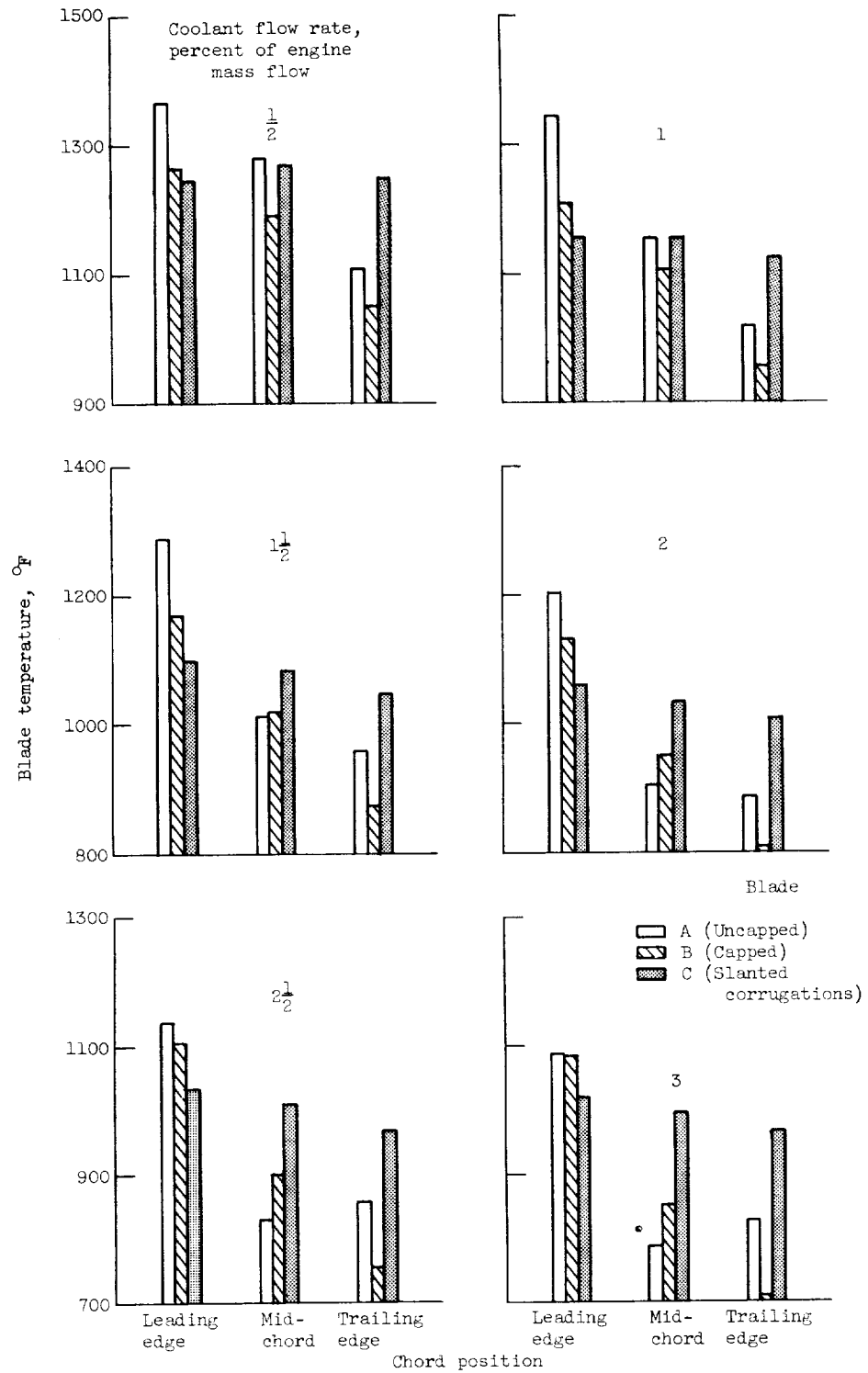


Figure 10. - Chordwise temperature gradients for three blade types investigated.

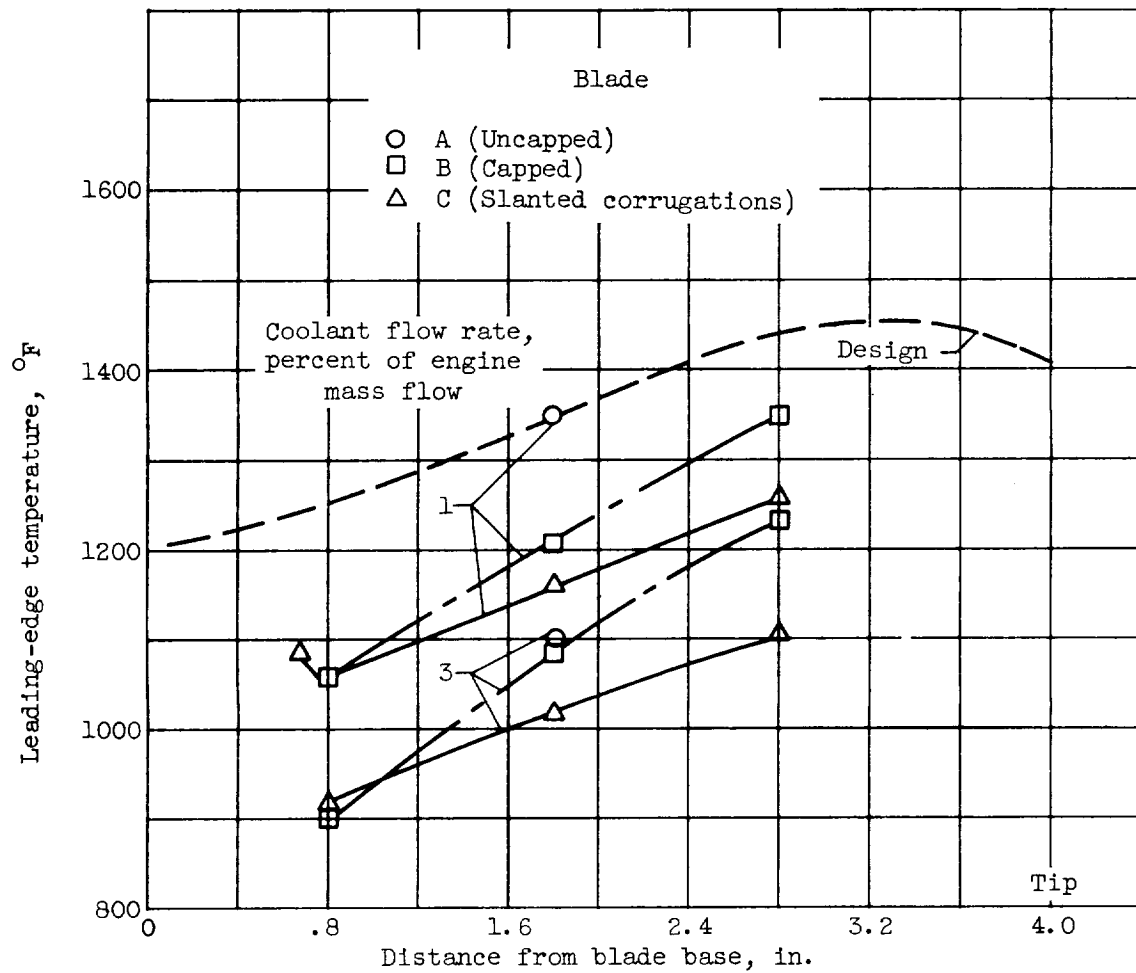


Figure 11. - Leading-edge spanwise temperature gradients for three blade types investigated.

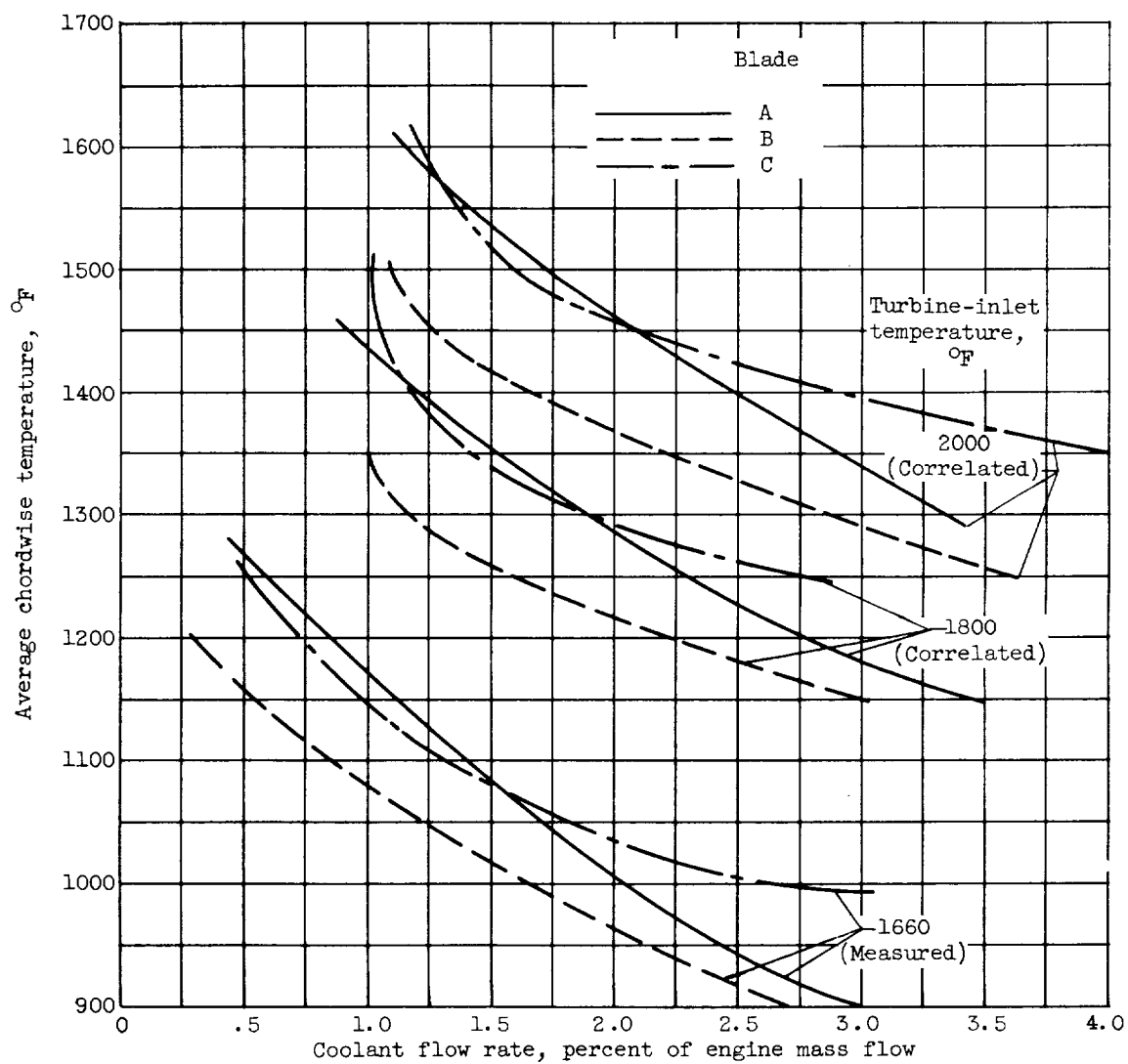


Figure 12. - Comparison of measured and correlated average chordwise temperatures for three blade types at turbine-inlet temperatures of 1660°, 1800°, and 2000° F.

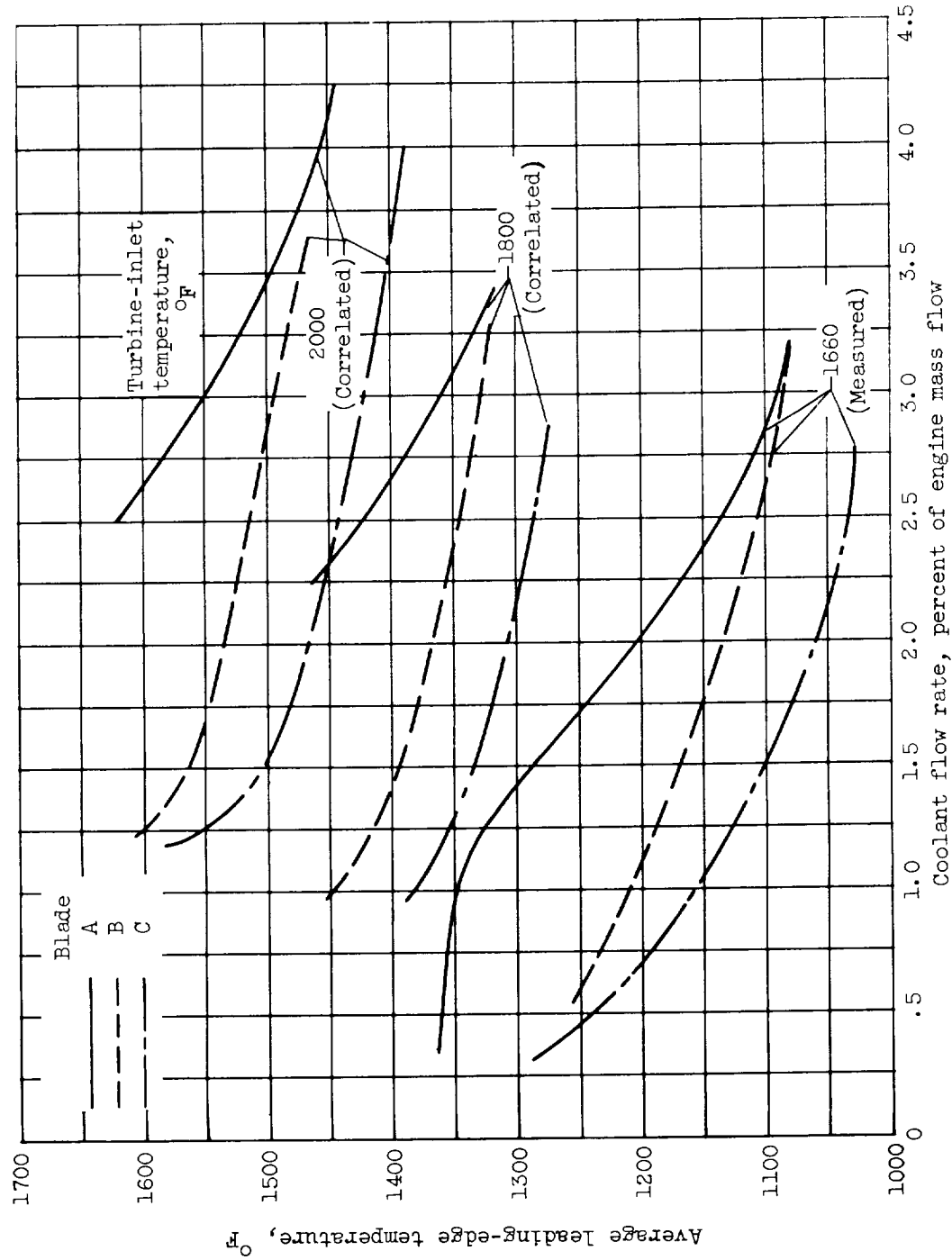


Figure 13. - Comparison of measured and correlated leading-edge temperatures for three blade types at turbine-inlet temperatures of 1660°, 1800°, and 2000° F.

<p>NASA MEMO 2-9-59E</p> <p>National Aeronautics and Space Administration. AIR-COOLED TURBINE BLADES WITH TIP CAP FOR IMPROVED LEADING-EDGE COOLING. Howard F. Calvert, André J. Meyer, Jr., and William C. Morgan. February 1959. 23p. diags., photo. (NASA MEMORANDUM 2-9-59E)</p> <p>(Title, Unclassified)</p> <p>Leading-edge tip caps substantially improved the cooling characteristics of air-cooled turbine blades. Data obtained at rated engine conditions were pro- jected by a correlation procedure to turbine-inlet temperatures of 1800° and 2000° F. Blades with tip caps could operate with acceptable coolant flows at these elevated turbine-inlet temperatures.</p>	<ol style="list-style-type: none">1. Engines, Turbojet (3. 1. 3)2. Turbine Cooling (3. 7. 2) <ol style="list-style-type: none">I. Calvert, Howard F.II. Meyer, André J., Jr.III. Morgan, William C.IV. NASA MEMO 2-9-59E	<p>NASA MEMO 2-9-59E</p> <p>National Aeronautics and Space Administration. AIR-COOLED TURBINE BLADES WITH TIP CAP FOR IMPROVED LEADING-EDGE COOLING. Howard F. Calvert, André J. Meyer, Jr., and William C. Morgan. February 1959. 23p. diags., photo. (NASA MEMORANDUM 2-9-59E)</p> <p>(Title, Unclassified)</p> <p>Leading-edge tip caps substantially improved the cooling characteristics of air-cooled turbine blades. Data obtained at rated engine conditions were pro- jected by a correlation procedure to turbine-inlet temperatures of 1800° and 2000° F. Blades with tip caps could operate with acceptable coolant flows at these elevated turbine-inlet temperatures.</p>	<ol style="list-style-type: none">1. Engines, Turbojet (3. 1. 3)2. Turbine Cooling (3. 7. 2) <ol style="list-style-type: none">I. Calvert, Howard F.II. Meyer, André J., Jr.III. Morgan, William C.IV. NASA MEMO 2-9-59E
<p>Copies obtainable from NASA, Washington</p>	<p>NASA</p>	<p>Copies obtainable from NASA, Washington</p>	<p>NASA</p>
<p>NASA MEMO 2-9-59E</p> <p>National Aeronautics and Space Administration. AIR-COOLED TURBINE BLADES WITH TIP CAP FOR IMPROVED LEADING-EDGE COOLING. Howard F. Calvert, André J. Meyer, Jr., and William C. Morgan. February 1959. 23p. diags., photo. (NASA MEMORANDUM 2-9-59E)</p> <p>(Title, Unclassified)</p> <p>Leading-edge tip caps substantially improved the cooling characteristics of air-cooled turbine blades. Data obtained at rated engine conditions were pro- jected by a correlation procedure to turbine-inlet temperatures of 1800° and 2000° F. Blades with tip caps could operate with acceptable coolant flows at these elevated turbine-inlet temperatures.</p>	<ol style="list-style-type: none">1. Engines, Turbojet (3. 1. 3)2. Turbine Cooling (3. 7. 2) <ol style="list-style-type: none">I. Calvert, Howard F.II. Meyer, André J., Jr.III. Morgan, William C.IV. NASA MEMO 2-9-59E	<p>NASA MEMO 2-9-59E</p> <p>National Aeronautics and Space Administration. AIR-COOLED TURBINE BLADES WITH TIP CAP FOR IMPROVED LEADING-EDGE COOLING. Howard F. Calvert, André J. Meyer, Jr., and William C. Morgan. February 1959. 23p. diags., photo. (NASA MEMORANDUM 2-9-59E)</p> <p>(Title, Unclassified)</p> <p>Leading-edge tip caps substantially improved the cooling characteristics of air-cooled turbine blades. Data obtained at rated engine conditions were pro- jected by a correlation procedure to turbine-inlet temperatures of 1800° and 2000° F. Blades with tip caps could operate with acceptable coolant flows at these elevated turbine-inlet temperatures.</p>	<ol style="list-style-type: none">1. Engines, Turbojet (3. 1. 3)2. Turbine Cooling (3. 7. 2) <ol style="list-style-type: none">I. Calvert, Howard F.II. Meyer, André J., Jr.III. Morgan, William C.IV. NASA MEMO 2-9-59E
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